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PROGRESS TOWARDS FIBRE OPTIC SMART STRUCTURES

Nezih Mrad

Defence R&D Canada – Atlantic

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The continued demand for high performance military platforms with reduced life cycle costs and extended operational lives is driving the development of autonomous systems and subsystems, advanced signal processing, smart sensors, and new generation materials. Autonomous systems, including autonomous structural health monitoring are expected to form an integral part of future military platforms. These systems heavily rely on an intelligent network of sensors for potentially reducing the high cost associated with platform ownership. Advanced sensor networks, including fibre optic sensors, are expected to significantly contribute to such effort. This document establishes progress made toward the development and application of fibre optic based sensor systems for military platforms. It identifies and documents activities and associated experiences within the Composites Technology and Performance Group of the Technical Cooperation Program (TTCP-MAT-TP7). The report that focuses on fibre optic smart structures, structural health monitoring, bonded patch repair monitoring, and composites process monitoring and manufacturing provides recommendation on the way forward for fibre optic smart structures development and implementation.

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Abstract

The continued demand for high performance military platforms with reduced operational cost and extended life cycle is driving the development of autonomous systems and subsystems, advanced signal processing, smart sensors, and new generation materials. Autonomous systems including autonomous structural health monitoring are expected to form an integral part of future military platforms. These systems heavily rely on an intelligent network of sensors for potentially reducing the high cost associated with platform ownership. Advanced sensor networks, including fibre optic sensors, are expected to significantly contribute to such effort.

This document establishes progress made toward the development and application of fibre optic based sensor systems for military platforms. It identifies and documents activities and associated experiences within the Composites Technology and Performance Group of the Technical Cooperation Program (TTCP-MAT-TP7). The report that focuses on fibre optic smart structures, structural health monitoring, bonded patch repair monitoring, and composites process monitoring and manufacturing, provides recommendation on the way ahead for fibre optic smart structures development and implementation.

Résumé

La demande continue pour les plates-formes militaires de haute performance à coût opérationnel réduit et à cycle de vie utile prolongé stimule le développement de systèmes et de sous-systèmes autonomes, de méthodes de traitement avancées des signaux, de capteurs intelligents et de matériaux de nouvelle génération. Les systèmes autonomes effectuant le contrôle d'état autonome des structures devraient faire partie intégrante des futures plates-formes militaires. Ces systèmes dépendent grandement d'un réseau de capteurs intelligent pour que le coût élevé relié à la possession de plates-formes soit potentiellement réduit. Les réseaux de capteurs perfectionnés, notamment de capteurs à fibre optique, devraient grandement contribuer à un tel effort.

Le présent document montre les progrès effectués en vue du développement et de l'application de systèmes de capteurs à fibre optique pour les plates-formes militaires. Il identifie et documente les activités et les expériences connexes dans le groupe de la technologie et des performances des matériaux composites du Programme de coopération technique (TTCP-MAT-TP7). Le rapport, qui traite principalement des structures intelligentes à fibre optique, du contrôle d'état des structures, du contrôle du rapiéçage collé et du contrôle des procédés relatifs aux composites et de leur fabrication, présente des recommandations sur la voie à suivre dans le développement et la mise en oeuvre des structures intelligentes à fibre optique.

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Executive summary

INTRODUCTION

Due to their high stiffness, light weight, and the flexibility to construct complex geometries, composite materials are witnessing unprecedented use in aircraft structures. The new concept of in-service aircraft structural health monitoring is also gaining a wider acceptance from airline manufacturers and operators. The concept that provides structures with a certain level of intelligence relies on embedded sensors for continuous in-service assessment of the state of the health and performance. To better understand the effectiveness of advanced sensors technology in the development of smart structures and its impact on military platforms, a review of the activities within the Composites Technology and Performance Group of the Technical Cooperation Program (TTCP-MAT-TP7) has been conducted.

RESULTS

The technology assessment review of the TTCP-MAT-TP7 activities focused on fibre optic smart structures and on their impact on advancing defence capability for reducing the cost of ownership. The review identified and documented activities and associated experiences of the TTCP-MAT-TP7 group, and it suggests that the application of fibre optic sensors is on the rise, particularly for military platforms. The review further concludes that the technology can readily be used to detect structural and repair damage growth, monitor platforms' structural state and provide monitoring capabilities for autoclave-based manufacturing processes.

SIGNIFICANCE

The evaluated technology will potentially lead to improved modes of operation, lower cost of ownership, and increased operational readiness. It will also ease the airworthiness requirements and contribute to the certification of new and advanced platform components. It will contribute to the implementation of network centric warfare with the development and implementation of smart "self-aware" platforms that are able to determine their current state and capability for mission delivery.

FUTURE PLANS

A potential assessment of fibre optic smart structures technology outside the scope of the TTCP is expected.

Mrad, N. 2004. Progress Towards Fibre Optic Smart Structures. TM 2003-200. DRDC Atlantic

Sommaire

INTRODUCTION

Étant donné leur grande rigidité, leur poids léger et leur capacité de prendre des formes géométriques complexes, les matériaux composites connaissent une utilisation sans précédent dans les structures d'aéronefs. Le nouveau concept de contrôle d'état des structures d'aéronef en service est de plus en plus accepté par les constructeurs et les exploitants d'avions de ligne. Le concept qui permet d'obtenir des structures dotées d'un certain niveau d'intelligence repose sur l'intégration de capteurs pour une évaluation en service continue de l'état et des performances. Afin de mieux comprendre l'efficacité de la technologie avancée des capteurs dans le développement de structures intelligentes et son incidence sur les plates-formes militaires, on effectue un examen des activités du groupe de la technologie et des performances des matériaux composites du Programme de coopération technique (TTCP-MAT-TP7).

RÉSULTATS

L'examen d'évaluation technologique des activités du TTCP-MAT-TP7 portait principalement sur les structures intelligentes à fibre optique et sur leur incidence en matière d'avancement des capacités de défense en vue de réduire le coût de possession. L'examen a permis d'identifier et de documenter les activités et les expériences connexes du groupe TTCP-MAT-TP7, et il semble indiquer que les applications des capteurs à fibre optique progressent, particulièrement dans le cas des plates-formes militaires. De plus, l'examen permet de conclure que la technologie peut facilement être utilisée pour détecter la progression de défauts de structure et des réparations requises, pour contrôler l'état de la structure des plates-formes et pour contrôler les procédés de fabrication en autoclave.

PORTÉE

La technologie évaluée pourra conduire à des modes d'exploitation améliorés, à une réduction du coût de possession et à une capacité opérationnelle accrue. De plus, elle atténuera les exigences de navigabilité et contribuera à la certification de nouveaux composants de plate-forme améliorés. Elle favorisera la mise en oeuvre de la guerre réseaucentrique par le développement et la mise en place de plates-formes intelligentes « auto-conscientes » qui peuvent déterminer elles-mêmes leur état et leur capacité à accomplir leur mission.

RECHERCHES FUTURES

On prévoit qu'une évaluation potentielle de la technologie des structures intelligentes à fibre optique sera menée en dehors du champ d'action du TTCP.

Mrad, N. 2004. Progress Towards Fibre Optic Smart Structures. TM 2003-200. DRDC Atlantic

Table of contents

List of figures

Acknowledgements

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1. INTRODUCTION

The continued demand for high performance military platforms with reduced life cycle costs and extended operational lives is driving the development of autonomous systems and subsystems, advanced signal processing, smart sensors, and new generation materials. It is estimated that about 40% and 60% of the weight associated with the newly introduced Joint Strike Fighter (JSF) and the Boeing 7E7 jetliner, respectively, is attributed to composite materials. Autonomous systems including autonomous structural health monitoring are expected to form an integral part of future military and air platforms. These systems heavily rely on intelligent networks of sensors for reducing the high ownership cost. Advanced sensor networks form the basis for smart structures development and advanced structures qualification and certification.

The concept of smart structures is being implemented on several platforms, including military ones. The concept shown in Figure 1, illustrates the requirement for the integration of sensors, actuators and advanced signal processing capabilities in the implementation of these structures. Several definitions of smart structures exist, one of which is: a smart structure is a structure that is "aware" of its state and its environment and having the ability to respond to changes induced by different stimuli in an intelligent way. Generally, such structures are known as intelligent or adaptive structures. The added intelligence is achieved by advanced processing of sensor information, "built-in" nervous systems, and intelligently driving actuators, "built in muscles", to bring the structure into its desired state.

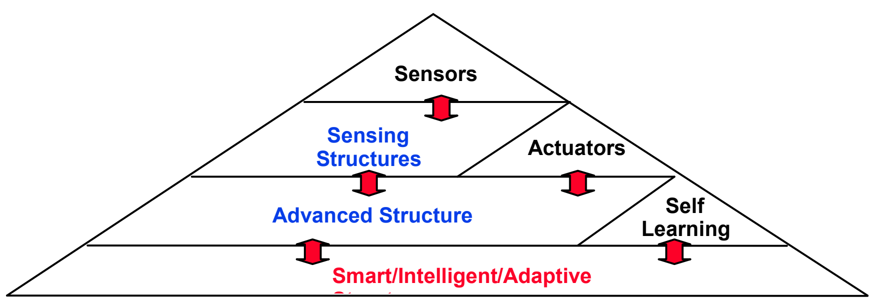


Figure 1: Smart structure concept

Sensors and actuators, and at times electronic signal processing and device controlling electronics, are integrated "embedded" into the structure to render it smart, intelligent and adaptive. Fibre optic sensors, piezoelectric sensors (piezoceramics (PZT) Polyvinylidene Floride (PVDF) films and polymers, nitinol fibre (NiTi) sensors, and microlectromechanical (MEMS) sensors are the well-known advanced sensors with potential for integration into smart structures. Structures with embedded fibre optic sensors are also known as fibre optic smart structures. Figure 2, illustrates a

schematic of a self-powered smart structure where sensors, actuator, signal processing, computation protocols and power sources form part of the overall structural system.

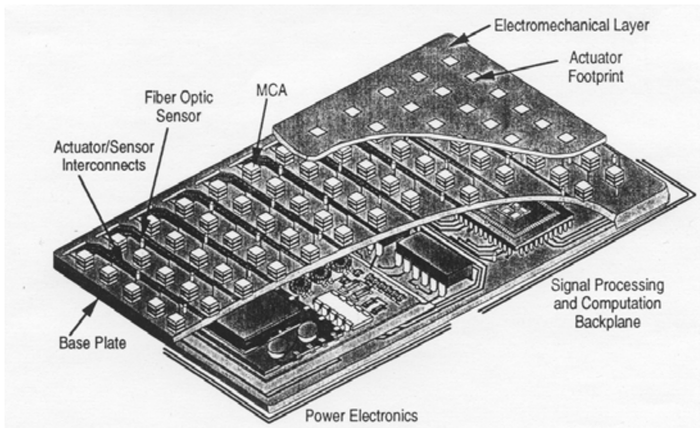


Figure 2: Example of an autonomous structure or "smart structure"

With the increasing usage of composite materials in military and civilian aircraft, advanced sensor technology is expected to play a significant role in enhancing safety and aircraft security, reducing aircraft manufacturing costs, as well as operating and maintenance costs, and assisting airworthiness authorities with quantitative assessment of aircraft integrity. Significant development in the area of fibre optic sensor technology has taken place in recent years and several sensor concepts and configurations have been developed [1]. This capability has been demonstrated to fill a gap that exists in the medical and communication sectors, as well as manufacturing and structural health monitoring of aircraft structures.

Benefits	**Concerns**
• Compact size • Lightweight • Flexibility • EM and RF immunity • High bandwidth • Remote sensing capability • Tolerance for extreme environments • Intrinsic safety • Low maintenance • High sensitivity • Distributed sensing potential • Passive effect on measured environment • Networking and multiplexing capabilities • Potentially inexpensive	• Moderate to high cost • Long term durability and reliability • Calibration difficulties • High system drift • Lack of standardization • Low demand • Existence of competing technologies **Constraints** • Technological (e.g. temperature compensation, signal handling, multiplexing, optical signal processing) • Demand (e.g. military continue to be the primary market)

Fibre optic sensors are a powerful class of sensors. They bring to the measurements and instrumentation communities what optical fibre cables have brought to the communication industry. The technology further offers the above benefits, concerns, and constraints. It is estimated [2] that the fibre optic sensor world market value will be about US$600 million by 2011, of which about US$16 million will be devoted to military and aerospace applications.

Due to the significant advantages and the technological potential presented by this technology in the delivery of smart structures related products (e.g. smart patches, advanced process control systems, autonomous structural health monitoring systems), in military platforms, The Composites Technology and Performance group of The Technical Cooperation Program (TTCP-MAT-TP7) has been investigating fibre optic smart structures activities within the TTCP member nations.

2. SCOPE AND OBJECTIVES

The objective of this report is to identify, review, document, and disseminate lessons learned, within the TTCP-TP-7-S24, in the development of fibre optic smart structures of military relevance. Based on the findings, recommendations are made on the way ahead for the development of fibre optic based smart structures.

3. RATIONAL FOR DEFENCE RELEVANCE

The move toward condition-based maintenance and in-service platform health assessment and monitoring promises a significant reduction in cost of military and civilian platforms' ownership. This cost saving will be achieved by the development and implementation of autonomous systems as components of the global smart structures concept. These structures that are composed of composite materials and contain integrated advanced sensor networks will provide in-service structural information leading to reduced costly periodic inspections, replacement and removal of components by cause, and reduced personnel and platform downtime. In the case of wide area coverage by sensor networks, size, weight, cost, power requirements, communications, reliability and performance all become issues for implementation. Fibre optic based sensors and sensor networks provide a promising and feasible approach to such issues.

This technology that will potentially lead to improved modes of operation, lower cost of ownership, and increased operational readiness will also ease the airworthiness requirements and contribute to the certification of new and advanced platform components. It will also contribute to the implementation of network centric warfare with the development and implementation of smart "self-aware" platforms that are able to determine their current state and capability for mission delivery.

Further benefits of this activity are to develop better understanding of platform performance, capabilities and technologies leading to improved mission planning and operation, enhanced maintenance schedules giving lower cost of ownership, and an increase in aircraft readiness and availability.

4. ACTIVITIES IN FIBRE OPTIC SENSOR TECHNOLOGY

Among several institutions and nations, TTCP-MAT-TP-7 has been conducting R&D activities in the integration of fibre optic sensor technology for use in structural and performance monitoring of composite structures and bonded repairs. Research efforts have focused mainly on the development, implementation and integration of two types of sensors: Fibre Fabry-Perot (FFP) and Fibre Bragg Grating (FBG) sensors. These efforts have a common goal of developing a cost-effective, reliable, in-situ damage monitoring system that would reduce the cost of a fibre optic smart structure, increase the operational readiness, and accelerate the certification process of the developed product (e.g. textile composites, smart patch, embedded micro-instrumentation). Selected sensor types have certain advantages and disadvantages, which are very well known from the literature [1].

Australia, Canada, United Kingdom and United States have contributed significantly to the application of fibre optic sensor technology to structural health monitoring, bonded patch repair and composite process monitoring and fabrication. Some of their activities are reported in the following sections.

4.1 Structural Health Monitoring

Both Fabry Perot and Bragg Grating sensors were successfully demonstrated for structural health monitoring of monolithic and composite structures. Figures 3 and 4 [3], illustrate the feasibility of employing Bragg Grating fibre optic sensors for static load monitoring and for crack growth monitoring onto monolithic structures, respectively. Research [4] has further demonstrated the feasibility of this sensor type for dynamic measurements and illustrated the sensor fatigue life and reliability under fatigue tests. It was reported that there was no Grating output degradation after 2 million cycles.

For static load monitoring, it was observed that the Bragg Grating sensor strain deviated from the theoretical value by 2.0%; whereas, the resistive strain gauges deviated by 2.3% with the worst case in the compression mode, as shown in Figure 3. Figure 4 further illustrates that fibre optic strain sensors can adequately monitor crack growth within a monolithic structure. The fibre optic sensor follows the same trend as that of the resistive strain gauge; however, its strain magnitude is affected by the 45^{o} crack propagation (not shown in figure).

Figures 5 and 6 [5], illustrate the feasibility of employing Extrinsic Fabry Perot Interferometric (EFPI) fibre optic sensor load and damage monitoring into 3-D woven preforms.

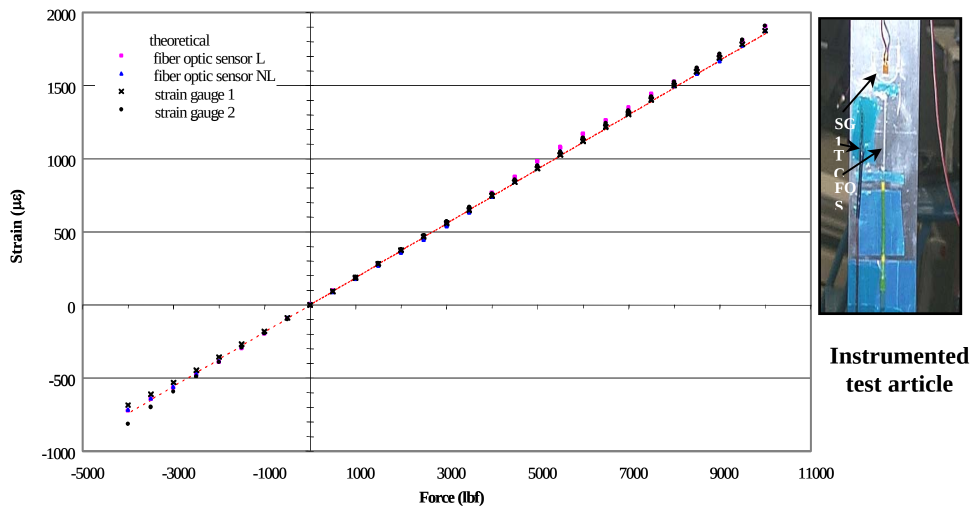


Figure 3: Static loading of an instrumented monolithic beam structure with resistive strain gauges (front – SG1 and back – SG2), Bragg Grating fibre optic sensor (FOS), and temperature sensor (TC).

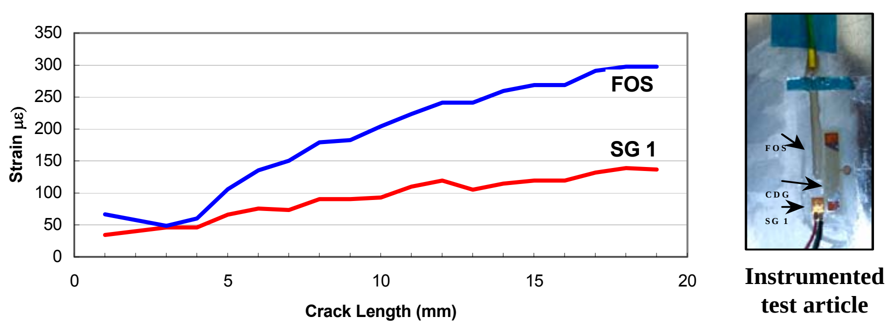


Figure 4: Crack growth monitoring in an instrumented monolithic beam structure with resistive strain gauge (SG1), Bragg Grating fibre optic sensor (FOS), and a crack detection gauge (CDG).

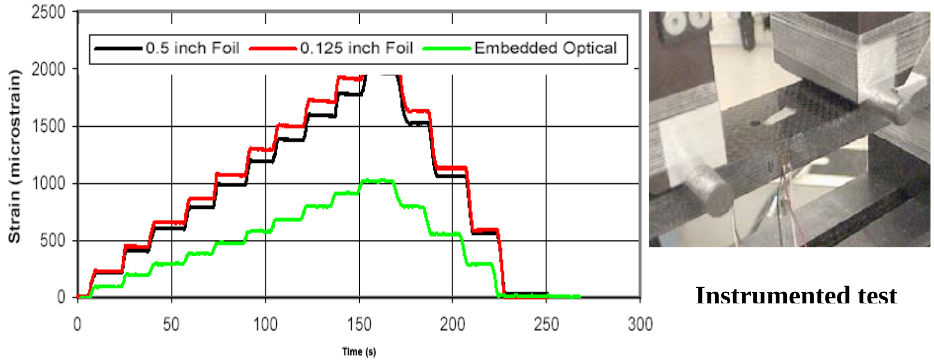


Figure 5: Strain monitoring in a four-point bend test of a 3-D woven preform of thickness 16.5 mm.

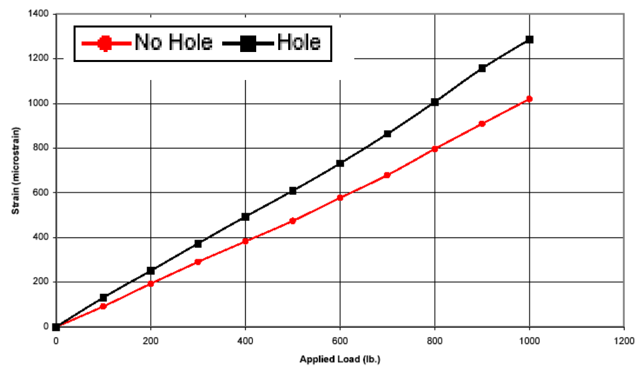
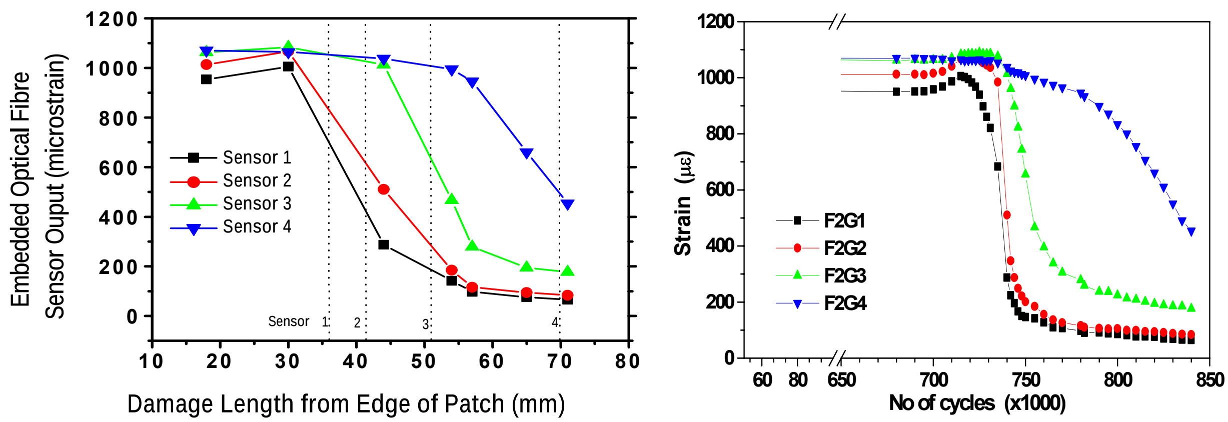


Figure 6: Artificially introduced damage monitoring in a 3-D woven preform.

For load monitoring, using the four-point bend test, it was observed (Figure5) that the highest strain was associated with the shorted resistive strain gauge that was mounted on the surface of the test specimen. The fibre optic sensor strain was the lowest due to the fact that the EFPI sensor was embedded near the neutral axis of the bend specimen. Figure 6, also illustrates that the EFPI can potentially be employed as a damage monitoring sensor. As the data illustrates, there is an increase in strain near the artificially introduced hole simulating damage.

4.2 Bonded Patch Repair Monitoring

Efforts on developing fibre optic based bonded repair health and integrity monitoring systems has focused mainly on the use of single and multiple Bragg Grating sensors. Figures 7(a) and 7(b) [6], illustrate the responses from four Bragg Gratings, multiplexed onto a single fibre, to artificially induced delamination within the repair patch and the patch adhesive/bondline.



(a) (b)

Figure 7: Response of embedded Bragg Grating sensors to artificially introduced damage within the patch and its adhesive bondline that is illustrated in Figure 8.

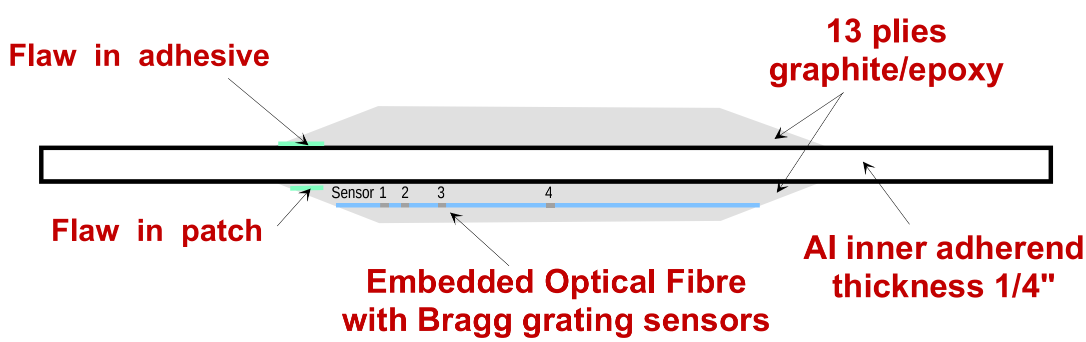


Figure 8: Schematic of embedded Bragg Grating sensor configuration and artificially induced patch delamination and disbond.

Figure 8 [6], shows the common specimen adopted by all member nations to evaluate conventional (resistive strain gauges) and advanced (fibre optic, piezoelectric, and MEMS) sensors for the development of "smart" patching technology. Figures 7 and 8, illustrate the potential effectiveness of the use of the highly multiplexed Bragg Grating sensors in the development of smart patching technology. As the damage progresses toward the center of the patch, consecutive Gratings become more sensitive to any growth of the damage that is illustrated by the decline in the sensor output. Sensor 4, placed at the center of the patch, picks up the damage after it has progressed significantly whereas sensors 1 and 2 are no longer affected by any damage progression.

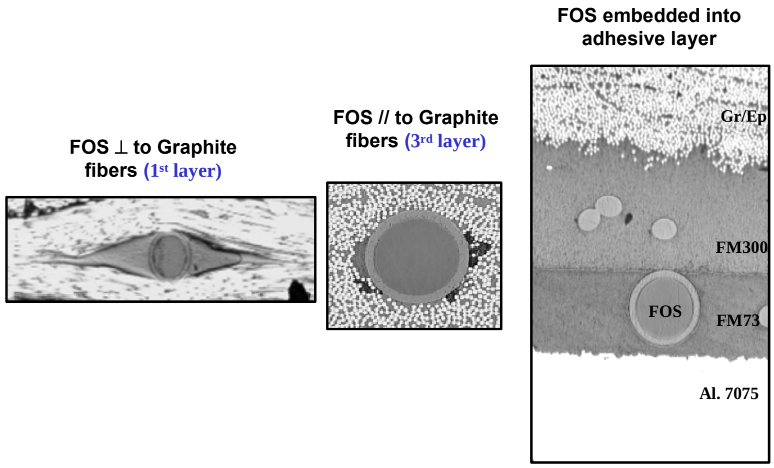


Figure 9: Embedded fibre optic sensor into composite patch and adhesive patch bondline.

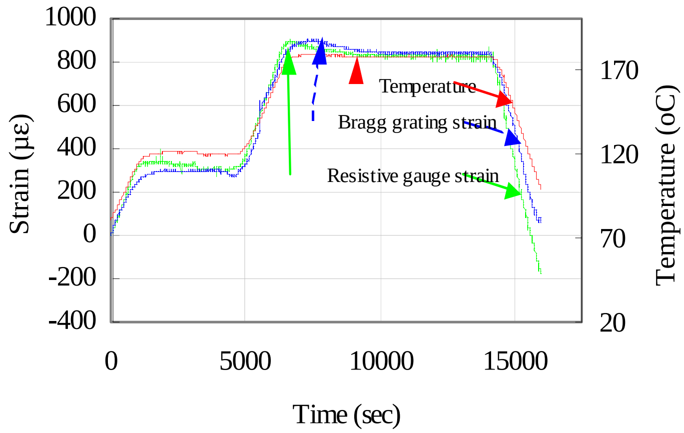
Other contributions to the development of advanced bonded repair technology have also focused on developing an understanding the effect of embedding the sensor into composite patches and adhesive bondline and its effect on the actual measurand. Figure 9 represents magnified views of a fibre optic sensor embedded into a composite patch and patch adhesive bondline, respectively. Qualitative assessment suggests that the sensor be placed parallel to the graphite fibre within the patch and along the longitudinal direction of the patch, within the adhesive bondline

4.3 Composites Process Monitoring and Manufacturing

Both Fabry-Perot and Bragg Grating sensors were used to enhance the manufacturing process of composite structures, develop advanced process control systems, and process monitoring tools. Among the member nations, however, only Bragg Grating sensors were evaluated for advancing autoclave process monitoring. Figure 10, demonstrates the feasibility of employing this technology to further improve the manufacturing process of composite parts and determine in-situ part quality for enhanced quality assurance and potential process modification for component residual stress reduction. The process-monitoring sensor can potentially be integrated with the control system for advanced process control, and could also be used for part structural monitoring during handling and operation. Understanding the sensor response to composites process monitoring will pave the way for potentially embedding this sensor type into the patch bondline for integrity monitoring and into composite structures for smart structures development.

Data presented in Figure 10, suggests good correlation between the embedded Bragg Grating sensor and the embedded resistive strain gauge. This figure further illustrates tension experienced at the first stage of the cycle and compression at the highest

temperature stage, indicating process monitoring. In-fibre temperature compensation will constitute a significant step in the proper signal analysis and interpretation.



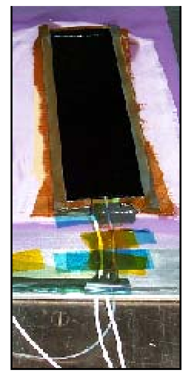


Figure 10: Response of an embedded Bragg Grating sensor to an AS4/3501-6 cure cycle during the processing of a composite panel.

5. CONCLUSIONS AND RECOMMENDATIONS

The proprietary nature of some of the work conducted within the TTCP organization, allowed limited access to the development in this area of interest. Nonetheless, the available information provided a very effective glimpse into some of the activities taking place and illustrated the importance of fibre optic sensors to smart structures, smart patches, and structural health monitoring system development. It further illustrated the feasibility of employing this technology for structural health monitoring, bonded patch repair, composites process monitoring, and fibre optic smart structures development.

It is believed that the technology, fibre optic smart structures, has significantly matured for civil applications, where miniaturization and reliability are not of critical concern. However, the technology requires further development to effectively penetrate the military and aerospace market. Some of the issues that require further development for accelerated acceptance of this emerging technology by aircraft manufacturers, owners and operators include the following:

1. Addressing robustness and long-term reliability of sensors and sensor systems, including electronics, within operating environments for the expected air platform life cycle (> 30 years).
2. Establishing a sensor self-sensing capability for redundancy reduction and sensor reliability enhancement.

3. Developing an understanding of sensor/host structures' interaction and influence of material constituents on sensor/structure performance and characteristics.
4. Developing technology, techniques and protocols for sensor protection at the ingress and egress points, while keeping in mind system integration and assembly.
5. Introducing robust, reliable, repeatable and accurate advanced manufacturing protocols without introducing additional manufacturing complexity, such as:
    a. frequent vacuum de-bulking of plies during lay-up for elimination of entrapped air and minimization of final part voiding and subsequent porosities;
    b. accommodation for complex autoclave/sensor interface; and
    c. accurate position of sensor within the composite component.
6. Establishing confidence measures for proper sensor and sensory system functioning.
7. Developing modeling and analysis tools for sensor/structures evaluation and proper signal interpretation and analysis.

Additional challenges and proposed approaches to overcome these challenges are further presented in [7].

The fact that much of the work conducted is of proprietary nature, illustrates that fibre optic smart structures are being developed and are of strategic importance to both civil and defence sectors. Effort must continue to establish confidence and improved reliability of the technology and exploit emerging micro- and nano-technologies to develop fibre optic smart structures and systems suitable for air platforms.

Due to the significant advantages and the potential presented by this technology for the delivery of smart structures related products (e.g. smart patches, advanced process control systems, intelligent in-situ structural health monitoring systems), it is recommended that focused research efforts, of high relevance to the military and defence communities, be initiated in the area of fibre optic smart structures. The suggested research initiatives should have the following objectives:

- Development of a better understanding of fibre optic sensor technology as it relates to the development of military smart structures related products and systems.
- Develop techniques, protocols, and subsystems for the eventual development of smart structures related products and systems (e.g. fibre optic based smart patching technology, advanced signal processing tools, enhanced modeling and analysis tools).
- Develop techniques for addressing the identified challenges and reducing sensor/system cost while enhancing its reliability and durability.
- Develop advanced integration protocols for providing cost effective autonomous systems.

- Address standardisation and certification issues to easily comply with airworthiness standards.

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The continued demand for high performance military platforms with reduced life cycle costs and extended operational lives is driving the development of autonomous systems and subsystems, advanced signal processing, smart sensors, and new generation materials. Autonomous systems, including autonomous structural health monitoring, are expected to form an integral part of future military platforms. These systems heavily rely on an intelligent network of sensors for potentially reducing the high cost associated with platform ownership. Advanced sensor networks, including fibre optic sensors, are expected to significantly contribute to such effort.

This document establishes progress made toward the development and application of fibre optic based sensor systems for military platforms. It identifies and documents activities and associated experiences within the Composites Technology and Performance Group of the Technical Cooperation Program (TTCP-MAT-TP7). The report that focuses on fibre optic smart structures, structural health monitoring, bonded patch repair monitoring, and composites process monitoring and manufacturing, provides recommendation on the way forward for fibre optic smart structures development and implementation.

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Composite structures, Smart Structures, fiber optic sensors, piezoelectric sensors, smart patching repairs.

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